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Suppression of J/ψ and ψ' Production in High-Energy Pb on Pb Collisions

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The anomalous J/ψ suppression in Pb-Pb collisions at 158A GeV observed recently by NA50 can be explained as due to the transition to a new phase of strong J/ψ absorption, which sets in when the local energy density exceeds about 3.4 GeV/fm^3.

High-energy heavy-ion collisions have become the focus of intense research because of the possibility of producing a quark-gluon plasma during such collisions [1,2]. The suppression of J/ψ and ψ' production has been suggested to probe the screening between a charm quark and a charm antiquark in the plasma [3,4]. While J/ψ and ψ' suppression has been observed [5–8], the phenomenon can be explained by absorption models without assuming the occurrence of the plasma [9–14].

Recently NA50 observed that the J/ψ and ψ' production is anomalously suppressed for Pb-Pb collisions at 158A GeV [15]. The observation led to a flurry of activities. While the present author and others presented theoretical findings at the Quark Matter '96 Meeting in May, 1996 [16–19], other theoretical studies have since been put forth [20,21]. A central question is whether the anomalous suppression in Pb-Pb collisions arises from the absorption by comovers (produced hadrons), as proposed by [19–21], or from the occurrence of a new phase of strong J/ψ absorbing matter (possibly a quark-gluon plasma), as suggested in [16–18]. The anomalous suppression of ψ' in Pb-Pb [15] and S-U collisions [7,8] is another question which needs to be addressed in the context of any possible occurrence of the new phase.

The study of these two questions requires the examination of absorption by soft particles not in the new phase, which is beyond the scope of the schematic model of [18]. Previously, a microscopic absorption model (MAM) was proposed which allows one to study the absorption by soft particles [11]. We shall use the MAM model to examine the two central questions outlined above. We show that contrary to the conclusions of [19–21], absorption by produced soft particles cannot explain the anomalous J/ψ absorption in Pb-Pb collisions; that a class of models with the feature of the occurrence of a new phase of strong absorption can explain the complete set of J/ψ data; and that ψ' is already anomalously absorbed by produced soft particle not in the new phase, and the transition to the new phase leads only to a small increase in ψ' absorption in Pb-Pb collisions.

We envisage that a produced (quasi-bound) $c\bar{c}$ pair evolving into J/ψ and ψ' states will collide with two types of particles. Collisions with baryons occur at high relative energies, and constitute the hard component of the absorption process. The absorption cross sections $\sigma_{\rm abs}(\psi N)$ and $\sigma_{\rm abs}(\psi' N)$ at high energies are approximately equal empirically [22], which can be understood by the Glauber picture of hadron-hadron collision [11]. The collisions of the $c\bar{c}$ with produced gluons or produced hadrons, which constitutes the soft component of absorption, occur at low relative energies of about 200 MeV, the temperature of produced particles. The breakup threshold is about 640 MeV for J/ψ and only about 50 MeV for ψ'. One expects the soft component to be small for J/ψ but large for ψ'. This is borne out by the data in Fig. 1 where $\mathcal{B}\sigma/AB$ is plotted (in logarithmic scale) as a function of $\eta = A^{1/3}(A-1)/A + B^{1/3}(B-1)/B$, which is approximately proportional to the average path length passing through nuclei A and B [2]. The absorption factor for the hard component is $\exp\{-\text{constant}\times\eta\}$. The absorption factor for the soft component is similarly $\exp\{-\text{constant}'\times\eta\}$ because the density of the produced soft particles is proportional to the longitudinal path length passing through nuclei A and B (see pages 374-377 of [2]). p-A collisions involve the hard component while A-B collisions involve both the hard and soft components [11]. The magnitude of the soft component is indicated by a gap and a slope change between the A-B line and the p-A line in Fig. 1. A large soft component

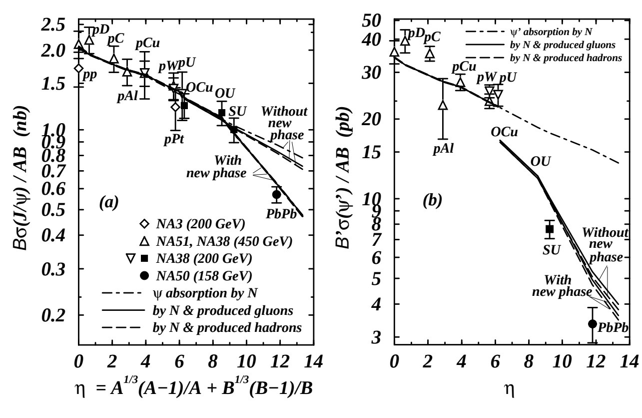

Fig.1. (*a*) $\mathcal{B}\sigma^{AB}_{J/\psi}/AB$ and (*b*) $\mathcal{B}'\sigma^{AB}_{\psi'}/AB$ as a function of η. Data are from NA3 [23], NA51 [24], NA38 [5,7,8], and NA50 [15].

for ψ' absorption is indicated in Fig. 1*b* by a large gap between the S-U point and the p-A line. A very small soft component for J/ψ absorption is indicated in Fig. 1*a*,

as there is almost no gap and no slope change between the p-A line and the A-B line joining the O-Cu, O-U, and S-U points. The A-B line passing the O-Cu, O-U and S-U points is much above the Pb-Pb point in Fig. 1a, indicating that the soft component constrained to explain the data of O-Cu, O-S and S-U cannot explain the anomalous J/ψ suppression in Pb-Pb collisions. A new source of absorption is suggested.

We shall further confirm the above observations using the microscopic absorption model (MAM). Adopting a row-on-row picture in the center-of-mass system and following straight-line space-time trajectories of the $c\bar{c}$'s, the baryons, and the centers of the fireballs of produced soft particles, the differential cross section for J/ψ production in an A-B collision is [11]

$$\frac{d\sigma_{J/\psi}^{AB}(\boldsymbol{b})}{\sigma_{J/\psi}^{NN}\, d\boldsymbol{b}} = \int \frac{d\boldsymbol{b}_A}{\sigma^2_{\rm abs}(\psi N)} \left\{ 1 - \left[1 - T_A(\boldsymbol{b}_A)\sigma_{\rm abs}(\psi N) \right]^A \right\} \times \left\{ 1 - \left[1 - T_B(\boldsymbol{b}-\boldsymbol{b}_A)\sigma_{\rm abs}(\psi N) \right]^B \right\} F(\boldsymbol{b}_A)\,, \quad (1)$$

where $T_A(\boldsymbol{b}_A)$ is the thickness function of nucleus A, and the soft particle absorption factor $F(\boldsymbol{b}_A)$ is

$$F(\boldsymbol{b}_A) = \sum_{n=1}^{N_<} \frac{a(n)}{N_> N_<} \sum_{j=1}^{n} \exp\{-\theta \sum_{i=1, i\neq j}^{n} (k_{\psi g} t_{ij}^g + k_{\psi h} t_{ij}^h)\}\,. \quad (2)$$

Here, $N_>(\boldsymbol{b}_A)$ and $N_<(\boldsymbol{b}_A)$ are the greater and the lesser of the (rounded-off) nucleon numbers $AT_A(\boldsymbol{b}_A)\sigma_{in}$ and $BT_B(\boldsymbol{b}-\boldsymbol{b}_A)\sigma_{in}$ in the row at $\boldsymbol{b}_A$ with an NN inelastic cross section σ_{in}, $a(n) = 2$ for $n = 1, 2, ..., N_< - 1$, and $a(N_<) = N_> - N_< + 1$. The quantities $\sigma_{\rm abs}(\psi m)$, the average relative velocity v_m, and the average number density ρ_m per NN collision always come together so that we can use the rate constant $k_{\psi m}$ ($m = g, h$) to represent their product. The interaction time t_{ij}^g (or t_{ij}^h) is the time for a J/ψ produced in collision j to overlap with the center of the fireball of gluons (or hadrons) produced in collision i at the same spatial point. They can be determined from $c\bar{c}$, g, h production time $t_{c\bar{c}}$, t_g, t_h, and the freezeout time t_f. The function θ is zero if $A = 1$ or $B = 1$, and is 1 otherwise. The expressions for ψ' production can be obtained from Eqs. (1-2) above by changing ψ into ψ'.

We first study $\mathcal{B}\sigma/AB$ data without the Pb-Pb points and compare them with theoretical models, including the possibility of absorption by soft particles: (A) absorption by baryons only, as in [9]; (B) by baryons and produced soft gluons, as in [11]; and (C) by baryons and produced soft hadrons (similar to [10] but differing in details and methods of evaluation). Following [11], we use $\sigma_{\rm abs}(\psi' N) = \sigma_{\rm abs}(\psi N)$ and search for $\sigma_{\rm abs}(\psi N)$ as well as $k_{\psi g}$ and $k_{\psi' g}$ in Model B, and $k_{\psi h}$ and $k_{\psi' h}$ in Model C, fixing the time constants to have the plausible values $t_g = 0.1$, $t_h = 1.2$, $t_f = 3$, and $t_{c\bar{c}} = 0.06$ (in units of fm/c). Different time constants will modify inversely the rate constants but will not affect greatly the product of the rate constants and their corresponding average interaction times. We take a Gaussian nuclear density for $A < 40$ and a Woods-Saxon density for $A \geq 40$. The curves marked "without new phase" in Fig. 1 are calculated with the parameters $\sigma_{\rm abs}(\psi N) = 6.94$ mb in Model A, and $\sigma_{\rm abs}(\psi N) = 6.36$ mb in Model B and C. In addition, $k_{\psi g} = 0.0956$ c/fm and $k_{\psi' g} = 3$ c/fm for Model B, and $k_{\psi h} = 0.0493$ c/fm $k_{\psi' h} = 3$ c/fm for Model C. As $k_{\psi g} << k_{\psi' g}$ in Model B and $k_{\psi h} << k_{\psi' h}$ in Model C, we confirm that the soft absorption component is small for J/ψ but large for ψ'.

When we include the Pb-Pb data point, no MAM calculations with a hard and a soft absorption component can simultaneously describe the whole set of J/ψ data. This suggests that there is a transition to a new phase of strong J/ψ absorption, when the local energy density exceeds a certain threshold. One can extend the MAM model to describe this transition. The energy density is approximately proportional to the number of collisions which has taken place at that point up to that time. We postulate that soft particles make a transition to a new phase of strong J/ψ absorption if there have been N_c or more baryon-baryon collisions at that point at time t_x. The quantity $k_{\psi g} t_{ij}^g + k_{\psi h} t_{ij}^h$ in Eq. (2) becomes $k_{\psi g} t_{ij}^g + k_{\psi h} t_{ij}^h + k_{\psi x} t_{ij}^x$, where the new rate constant $k_{\psi x}$ describes the absorption of J/ψ by the produced soft matter in the new phase. Here, $t_{ij}^x = t_n + t_h - t_x$ where t_n is the last NN collision time at that point and t_{ij}^x is the time for a J/ψ produced in collision j to overlap with the center of the fireball of absorbing soft particles produced in i in the form of the new phase, before hadronization takes place. We vary N_c and $k_{\psi x}$. Baryons passing through the spatial region of the new phase may also become deconfined and may alter their ψ-N absorption cross section. Accordingly, we also vary the effective absorption cross section, $\sigma_{\rm abs}^x(\psi N)$, for ψ-N interactions in the row in which there is a transition to the new phase, while $\sigma_{\rm abs}(\psi N)$ remain unchanged in other rows. The curves marked "with new phase" in Fig. 1 are obtained with the parameters $N_c = 4$, $k_{\psi x} = 1$ c/fm, and $\sigma_{\rm abs}^x(\psi N) = 14$ mb. The location where the slopes of the curves changes sharply is sensitive to N_c. The absorption of J/ψ saturates for $k_{\psi x} \geq 1$ c/fm for which the absorption is still slightly insufficient to account for the total J/ψ absorption; additional absorption with $\sigma_{\rm abs}^x(\psi N) = 14$ mb is needed to give Pb-Pb result to agree with experiment. The results for the cases with the new phase agree with the whole set of J/ψ data. We note that $k_{\psi x} >> k_{\psi g}, k_{\psi h}$.

The above MAM results can be expanded to obtain J/ψ and ψ' yields as a function of impact parameter b. The theoretical ratio $\mathcal{B}\sigma_{J/\psi}^{AB}/\sigma^{AB}(DY)_{2.9-4.5}$ for Drell-

Yan cross section in the interval $2.9 < M_{\mu^+\mu^-} < 4.5$ GeV can then be expressed in terms of $\mathcal{B}\sigma^{pp}_{J/\psi}/\sigma^{pp}(DY)_{2.9-4.5}$ for pp collisions, which was determined by NA51 to be 44±3 [15]. NA38 and NA50 used a geometrical model to obtain a relation between E_T and b [7,15], which can be used to transform the MAM results from a function of b to a function of E_T. In Fig. 2a we show theoretical $\mathcal{B}\sigma^{AB}_{J/\psi}/\sigma^{AB}(DY)_{2.9-4.5}$ as a function of E_T for S-U which agree with experiment within 5-10%, whether we assume a new phase or not. On the other hand, good agreement with Pb-Pb data is obtained only when we allow for the transition to a new phase of strong J/ψ absorption (Fig. 2b).

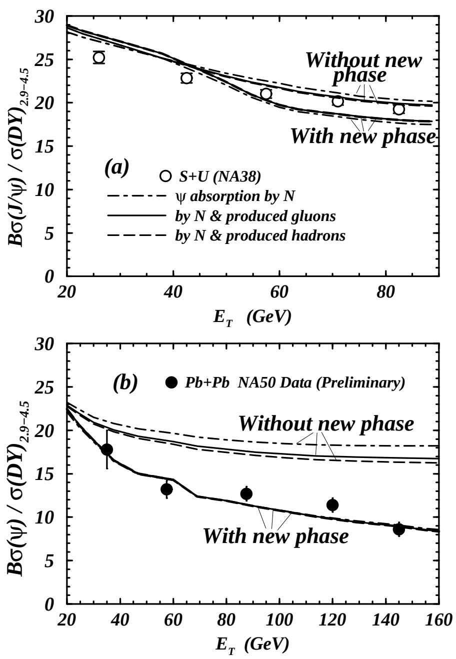

Fig.2. $\mathcal{B}\sigma^{AB}_{J/\psi}/\sigma(DY)_{2.9-4.5}$ as a function of E_T for (a) S-U collisions, and (b) Pb-Pb collisions. Data are from NA38 [8] and NA50 [15].

The results in Fig. 1b indicate that ψ' is already anomalously absorbed by soft particles in S-U and Pb-Pb collisions, even without the new phase. The occurrence of the new phase with $k_{\psi' x} = 3$ c/fm leads only to a small additional ψ' absorption in Pb-Pb collisions (Fig. 1b). We can calculate $\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(J/\psi)$ and compare with experiment. Fig. 3b shows that the experimental data for Pb-Pb collisions is consistent with the assumption of transition to the new phase. For S-U collisions, the theoretical results agree with experimental data for small and moderate values of E_T, but deviate from experimental data for large E_T (Fig. 3b). As large transverse energies involve greater weights for the major axis of the U nucleus to lie along the beam direction, the deviation of $\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(J/\psi)$ in S-U collisions at high E_T may be a deformation effect which can be tested experimentally by studying S-Pb collisions. The deformation effect can be utilized to study matter in the new phase by focusing on high E_T events in U-U collisions.

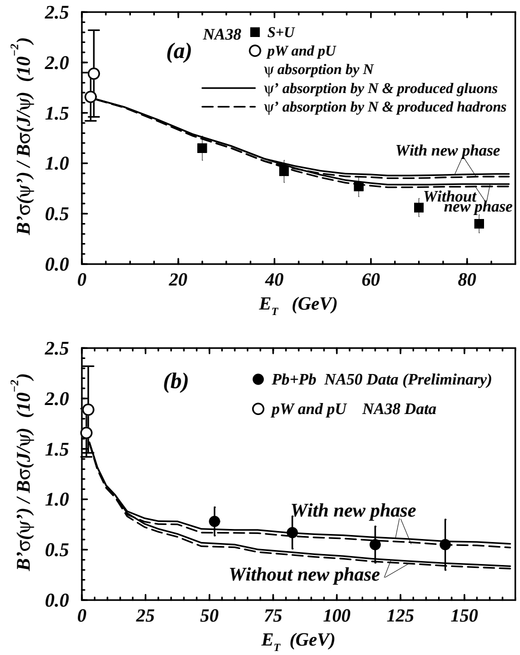

Fig.3. $\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(\psi)$ as a function of E_T for (a) S-U collisions and (b) Pb-Pb collisions. The data for p-W and p-U collisions are also included. Data are from NA38 [8,7] and NA50 [15].

What is the threshold energy density for the transition? We consider a row with a transverse area σ_{in} and with collision points separated longitudinally by d/γ, where $d = 2.46$ fm is the internucleon spacing and $\gamma = \sqrt{s}/2m_{\rm nucl} = 9.2$ is the Lorentz contraction factor at the Pb-Pb collision energy. Consider also N_c number of NN collisions at each collision point. Each NN collision leads to a fireball of soft particles with $dn^{NN}/dy \sim 1.9$ at the Pb-Pb collision energy [25]. At the time $t = d/\gamma$ after these N_c collisions, the produced soft particles leaving the fireballs at one collision point to the adjacent collision point will be compensated by soft particles arriving from the fireballs of the adjacent collision point, and a steady-state initial energy density is reached after $t = d/\gamma$ (before longitudinal expansion), with the energy density given approximately by $N_c(dn^{NN}/dy)m_t/(\sigma_{in}d/\gamma)$, where $m_t = 0.35$ GeV is the pion transverse mass. Hence, for $N_c = 4$ from the present study, the threshold energy density for the new phase is $\epsilon_c \sim 3.4$ GeV/fm^3, which is close to the quark-gluon plasma energy density, $\epsilon_c \sim 4.2$ GeV/fm^3, calculated from the lattice gauge result $\epsilon_c/T_c^4 \sim 20$ [26] with $T_c \sim 0.2$ GeV. Therefore, it is interesting to speculate whether the new phase of strong J/ψ absorption may be the quark-gluon plasma. In the equilibrated or non-equilibrated quark-gluon plasm, J/ψ production is expected to be greatly suppressed [3,27]. Furthermore, when baryons pass through the region of

the new phase, the baryon matter may be deconfined. The total cross section between a $c\bar{c}$ system and a baryon system is substantially enhanced when the quarks in the baryon are deconfined [28].

Our results for the cases with soft particle absorption differ qualitatively from those of [19–21]. We would like to mention some of the reasons for the differences. In Refs. [19,20], the soft particle absorption factor is approximately the form $\exp\{-\text{constant} \times E_T(b)\}$. This is obtained in [19] by assuming the density of produced soft particles to be $n(b) = \text{constant} \times E_T(b)$. Ref. [19] assumes $n(b) = \text{constant} \times G(b) E_T(b)$ and finds $G(b)$ to be independent of b. However, $E_T(b)$ contains contributions coming from the whole volume of NN collisions of the participant nucleons, which decreases significantly as b increases. When this volume $V(b)$ (in the C.M. system) is taken into account, the proper relation should be $n(b) = \text{constant} \times E_T(b)/V(b)$. The additional $V(b)$-type dependence in $n(b)$ will modify the results of [19,20]. Fig. 2 of the numerical cascade model of [21] gives a resultant J/ψ absorption factor for J/ψ absorption due to baryons in S-W collisions to be smaller than that in p-W collision at the same impact parameter of 2 fm. The authors of [21] should check whether these results are consistent with intuitive understanding and analytic results for absorption due to baryons. Clearly, much work remains to be done to resolve the differences.

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